Draft version August 14, 2006
Preprint typeset using LaTeX style emulateapj v. 6/22/04

THE STELLAR POPULATION OF STRIPPED CLUSTER SPIRAL NGC 4522: A LOCAL ANALOG TO K+A GALAXIES?

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Draft version August 14, 2006

ABSTRACT

We present observations of the stripped Virgo Cluster spiral NGC 4522, a clear, nearby example of a galaxy currently undergoing ISM-ICM stripping. Utilizing SparsePak integral field spectroscopy on the WIYN 3.5m telescope and GALEX UV photometry, we present an analysis of the outer disk ($r > 3$ kpc) stellar population of this galaxy, beyond the HI and Hα truncation radius. We find that the star formation in the gas-stripped outer disk ceased very recently, ~ 100 Myr ago, in agreement with previous claims that this galaxy is currently being stripped. At the time of this stripping, data and models suggest that the galaxy experienced a modest starburst. The stripping is occurring in a region of the cluster well outside the cluster core, likely because this galaxy is experiencing extreme conditions from a dynamic ICM due to an ongoing sub-cluster merger. The outer disk has a spectrum of a K+A galaxy, traditionally observed in high-redshift cluster galaxies. In the case of NGC 4522, a K+A spectrum is formed by simple stripping of the interstellar gas by the hot intracluster medium. These data show K+A spectra can be created by cluster processes and that these processes likely extend beyond the cluster core.

Subject headings: galaxies: spiral, galaxies: clusters: individual (Virgo), galaxies: individual (NGC 4522), galaxies: evolution

1. INTRODUCTION

K+A galaxies (Dressler & Gunn 1983), originally discovered in clusters at high redshift, differ from typical elliptical, spiral or irregular galaxies in an important way. These galaxies have spectra characterized by strong Balmer absorption lines and no significant emission from ongoing star formation. While the formation mechanisms of K+A galaxies are still unknown (Tran et al. 2003; Poggianti 2004; Bekki et al. 2005; Goto 2005), these spectra are generally interpreted as the signature of recent cessation of star formation (however, c.f. Burstein et al. 2005). Shioya et al. (2002) show through star formation models that such cessation and passive evolution of the already-existing population can form a K+A spectrum. While the interpretation of these spectra as the result of temporally truncated star formation is largely accepted, the cause of the termination of star formation is not settled.

Such catastrophic interruption of star formation seems likely to be caused by external processes. Events such as mergers, galaxy harassment, and ram pressure stripping all have the potential to terminate star formation. While K+A galaxies have been chiefly observed in clusters, observations of K+A spectra in lower density environments (i.e. Zabludoff et al. 1996; Tran et al. 2004; Goto 2005) show that they are not unique to the cluster environment. What role does environment play in the creation of these galaxies?

In the Virgo cluster, many spirals have truncated Hα disks (Koopmann & Kenney 2004), suggesting that ram pressure stripping has cut off the star formation in the outer disk. These galaxies have normal star formation inside a truncation radius, with no detected star formation at larger radii. The truncation location varies from galaxy to galaxy, with some galaxies moderately truncated inside $0.8R_{25}$ and others more severely truncated inside $0.4R_{25}$. In these galaxies, it is possible to measure age-sensitive absorption lines from the stellar populations beyond the truncation radius without contamination of emission lines from star-forming regions. The ages of the youngest stellar population in the outer disk tells us how much time has elapsed since the last epoch of star formation and, therefore, the time elapsed since the gas was removed. This, combined with the galaxy's location in the cluster, can tell us where in the cluster galaxies are stripped of their star-forming gas.

NGC 4522 is one of the clearest examples of ongoing ISM-ICM stripping observed in the nearby Virgo cluster. It is a highly inclined, $0.5L_*$ Sc galaxy $3^\circ.3$ ($1.3r_{200}$) south of M87, in a region of the cluster with modest ICM density (as measured from X-ray emission from Böhringer et al. 1994). There are several lines of evidence that NGC 4522 is experiencing ongoing ICM pressure. Despite an undisturbed stellar disk, the HI and Hα emission are spatially truncated in the disk at r=3 kpc=0.4 R_{25} and significant amounts of extraplanar HI and Hα emission exist on one side of the disk close to the truncation radius (Kenney & Koopmann 1999; Kenney et al 2004). A ridge of highly polarized radio continuum emission is observed in the disk opposite the extraplanar gas, suggesting compression of the magnetic field lines at the leading edge of the ISM-ICM interaction (Vollmer et al 2004). These data are consistent with a galaxy currently undergoing ram pressure; comparison of simulations and observations (Vollmer et al. 2006) suggest that we are observing this galaxy at a time close to peak pressure.

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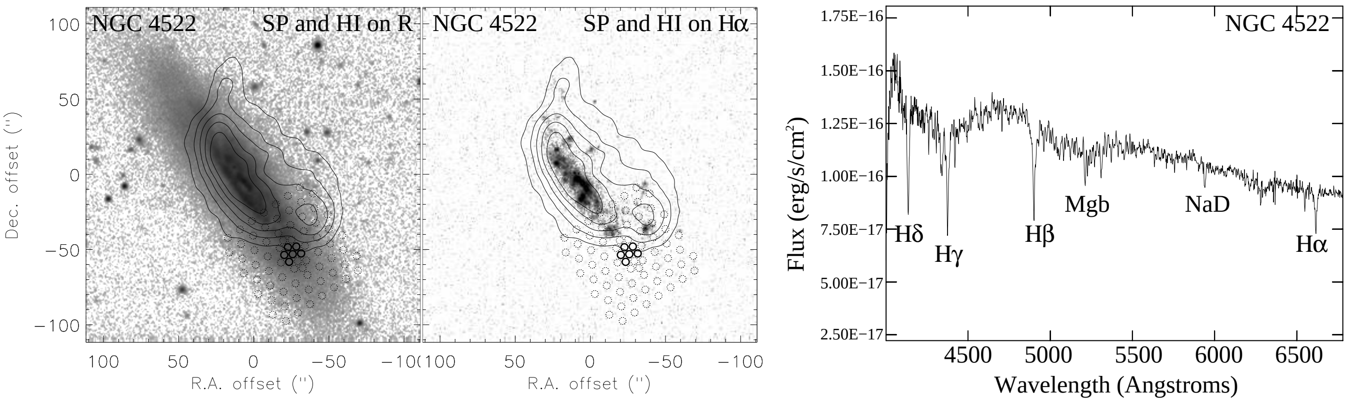

Fig. 1.— Left: R band image of NGC 4522, with the position of the SparsePak fibers superimposed over the image. Middle: Hα image of NGC 4522, with HI contours (Kenney et al 2004) and the SparsePak footprint overlayed. In both figures, the outlines of the fibers used to form the composite spectrum are bold. Right: Optical spectrum, resulting from the combination of several fibers just beyond the gas truncation radius.

2. OBSERVATIONS

2.1. *Optical Spectroscopy*

NGC 4522 was observed with the SparsePak integrated field spectrograph (Bershady et al 2004) on the WIYN 3.5m telescope during the night of March 29-30, 2003. SparsePak has 75 object fibers, each with a diameter of 4.″7, spread over an 80″ x 80″ region of the sky. The fiber spacing for most of the array is 10.″3 , except for a denser central core where the fibers have a center-to-center spacing of 5.″6 The SparsePak bundle was positioned with the majority of the fibers located beyond the Hα truncation radius (Figure 1). We followed standard IRAF image reduction techniques and used the `dohydra` task to extract the spectra, determine the wavelength solution, and subtract sky light. The data were then flux calibrated using spectrophotometric standards. The resulting data have a resolution of 5.5 Å(FWHM). Following the complete reduction of the spectral data, the spectrum from each fiber was examined to determine the quality of the data. The Hα truncation radius determined by spectroscopy matches the imaging data. We combine six fibers with no Hα emission and high signal-to-noise just beyond the gas truncation radius to create a higher signal-to-noise composite spectrum (Figure 1). These spectra sample a region along the major axis to the SW between 45″(3.5 kpc[1]) and 60″(4.5 kpc), within 5″(380 pc) of the major axis. These fibers all show Hα absorption from the underlying stellar population and no apparent Hα emission. All stellar population results presented here are based on this averaged spectrum. From these data, we extract absorption line indices based on the Lick/IDS definitions[2] (Faber et al. 1985).

2.2. *GALEX Photometry*

Observations of NGC 4522 were conducted with GALEX as part of that instrument's All Sky Survey (Martin et al. 2005). NGC 4522 was observed for 0.1ksec in both the FUV and NUV channels. Using a series of circular apertures chosen to match SparsePak fiber positions, we have extracted FUV and NUV fluxes for the same 1 kpc region along the major axis where we extract optical spectra. We combine these data with F606-band ($\sim V$) HST optical imaging (Kenney et al 2006) to determine FUV-to-optical and FUV-to-NUV flux ratios. Note that, because this region has been stripped of its gas and dust, the UV fluxes and colors are minimally affected by internal dust absorption.

3. RESULTS

3.1. *Properties of the Stripped Region*

The optical spectrum of NGC 4522 is very blue, with the continuum continuing to rise all the way to the blue spectral limit, unlike the red spectrum of a typical elliptical galaxy. This implies that the light from the galaxy is dominated by young stars. This observation is in agreement with the strong Balmer absorption in the outer disk of NGC 4522. We see strong absorption not only in Hβ, but also in the higher order lines: Hγ and Hδ, lines characteristic of a young, A-star-dominated population. If we compare this spectrum with those observed at higher redshift, we find a striking similarity to K+A galaxies. Dressler et al. (1999) quantify K+A galaxies as those galaxies with no significant star-forming emission[3] and strong Hδ absorption (EW(Hδ)$>$ 3 Å). The outer disk of NGC 4522 clearly fits this description, with no significant Hα emission and EW(Hδ)=5.2 Å.

The UV colors of this region show a similar signature: a nearly flat spectrum extends from the FUV band ($\lambda_{\rm eff} \sim$ 1500 Å) to the F606 band ($\lambda_{\rm eff} \sim$ 5900 Å). In particular, NGC 4522 is brighter in the GALEX FUV bandpass than in the NUV passband by a modest but significant amount ($F_{\rm FUV} = 3.9 \times 10^{-16}$ erg/s/cm^2/Å vs. $F_{\rm NUV} = 3.0 \times 10^{-16}$ erg/s/cm^2/Å). Because the FUV flux fades quickly in an evolving stellar population (e.g. Bruzual & Charlot 2003), the bright FUV emission from the outer disk implies a very young stellar population.

3.2. *Stellar Population Models*

Spiral galaxies are typically characterized by ongoing star formation. In the case of the stripped spiral galaxies

[1] We assume a distance to Virgo of 16 Mpc.

[2] Note that the data are *not* smoothed to the Lick resolution, but that we simply use the Lick feature wavelength definitions.

[3] Dressler et al. (1999) and many others use [OII]3727 as their indicator of star formation activity. As our spectral coverage does not extend blueward of 4000 Å, we use Hα as our star formation diagnostic.

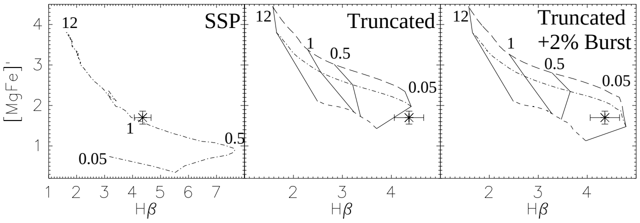

FIG. 2.— Index diagrams for Starburst99 models for an SSP (left), temporally truncated star formation (middle), and temporally truncated star formation with a 2% starburst at the time of truncation (right). Shown are the data (star) and models (lines) for the age-sensitive Hβ line plotted against the metallicity-sensitive [MgFe]′ index. The Starburst99 model plotted in the SSP figure (left) is for solar metallicity, with ages in Gyr marked along the line. In each of the other two figures (middle and right), the solid lines correspond to lines of constant truncation age, while the broken lines correspond to lines of constant metallicity (Z=0.008 (short dash), Z=0.02 (dot-dash), Z=0.04 (long dash)).

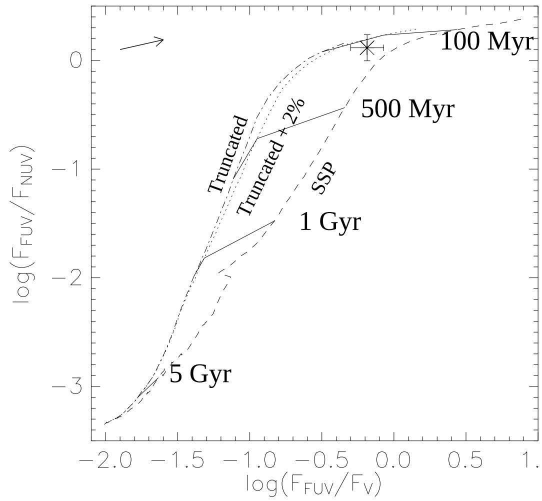

FIG. 3.— UV-optical colors derived for the models shown in Figure 2: SSP (dashed line), temporally truncated (dash-dot line), and truncated with 2% burst (dotted line). The solid lines correspond to ages of (from top to bottom) 100 Myr, 500 Myr, 1 Gyr and 5 Gyr. The value of the flux ratios for NGC 4522 is plotted as a asterisk. A representative reddening vector (determined from the results of Calzetti 1997 and using a value of E(B-V)=0.02 from Schlegel et al. 1998) is shown in the upper left section of the plot.

in Virgo, it's natural to assume a temporally truncated star formation history: roughly constant star formation, followed by abrupt cessation of star formation and passive evolution of the already-existing population. If one assumes a (temporally) truncated star formation history, the youngest (and brightest) stellar population will dominate the light, but there will be some "pollution" from the older stellar population. While the Balmer lines from the integrated light will be strong in this population, their strength will be somewhat diluted by the older population. In contrast, models assuming a "single burst" star formation history (a so-called "Simple Stellar Population" or "SSP"), will have stronger Balmer lines for $\sim$ 1 Gyr, the approximate lifetime of the Balmer-line-dominating A stars. This means that, for a given set of Balmer line indices, the last epoch of star formation in the temporally truncated model will always be *younger*[4] than the age of the SSP model. The GALEX UV data are, therefore, critical for constraining the age of the stellar population. The detection of bright, FUV flux in the outer disk of NGC 4522 demonstrates that the stellar population is very young.

Due to the presence of very young stars in the outer disk of NGC 4522 and the lack of young, metal-poor stars in empirical libraries, we have chosen to use Starburst99 models (Leitherer et al. 1999), with theoretical stellar atmospheres (Martins et al. 2005). Starburst99 generates SSP models with a range of ages and the sum of several theoretical spectra are used to model a truncated star formation history. The spectra are then smoothed to the resolution of our data (5.5ÅFWHM) and spectral line indices and broadband photometric colors are extracted. In Figure 2, we plot the strength of the age-sensitive Balmer features against the strength of the metallicity-sensitive [MgFe]′ index for a SSP, a set of temporally truncated star formation models, and a set of temporally truncated models in which 2% of the stellar mass formed in a burst at the end of the star forming episode. In Figure 3, we plot broadband UV and optical flux ratios for same three star formation histories.

[4] Any "age" referred to with respect to the temporally truncated star formation model is the age of the youngest generation of stars; *not* the luminosity weighted mean age of the population.

3.3. *Time Since Outer Disk Truncation*

The GALEX UV photometry (Figure 3) and optical spectroscopy (Figure 2) are best fit by an temporally truncated Starburst99 model, with a cessation age of $\sim$ 100 Myr. This is based on the combination of strong Balmer absorption and bright FUV emission in the outer disk. Either the optical spectroscopy or the GALEX photometry, when taken independently, can be fit by various models. The Balmer absorption lines indicate that either the stellar population is younger than a 50 Myr truncated star formation model *or* as old as a 1 Gyr SSP. Truncation is clearly the more logical star formation history, and we find the GALEX colors are far too blue for a 1 Gyr SSP; in fact, the GALEX data is most consistent with being truncated $\sim$ 100 Myr ago, an estimate that is relatively unaffected by reddening due to the fact that the reddening vector is nearly parallel to the line of constant age (Figure 3). While the Balmer lines are stronger than any simple truncated stellar population model, a modest 2% (by mass) starburst is enough to bring the absorption line data and GALEX data into agreement (Figure 2). Taken together, the data exclude a SSP star formation history and show roughly constant star formation in the outer part of NGC 4522 until $\sim$ 100 Myr ago, when there was a modest starburst, followed by the current period of no star formation and passive stellar evolution. This scenario is consistent with the observations that this is a spiral galaxy currently being stripped of its neutral gas (Kenney et al 2004; Vollmer et al. 2006) and with Hα observations suggesting that the inner disk has a moderately enhanced star formation rate (Kenney et al 2004).

4. DISCUSSION

Our results clearly show that the cessation of star formation was recent and, therefore, that the outer disk of NGC 4522 was recently stripped of its star-forming gas. We would like to understand how rapidly star formation stops during an interaction with the ICM and how long dense molecular star-forming clouds might survive after the low-density atomic gas is stripped. Simulations (Vollmer et al. 2006) compared with the HI observations (Kenney et al 2004) suggest that we are observing the galaxy ~ 50 Myrs after peak pressure. This timescale is consistent with that determined from the stellar population, suggesting that neutral gas stripping and termination of star formation nearly coincide.

4.1. *Stripping Outside the Cluster Core*

From a simple timescale argument, the stellar populations of NGC 4522 tell us that this galaxy must be stripped locally, 0.9 Mpc ($1.3r_{200}$) from M87, as opposed to closer to the cluster core. If we assume that the galaxy's motion in the plane of the sky is a factor of 2 higher than the average radial velocity of a Virgo Cluster galaxy (i.e. we assume $v_{\rm t} = 1400$ km/s), it would still take the galaxy ~ 500 Myr to travel the ~ 0.75 Mpc that separates its current location from the region where the ICM density is high enough to strip the outer disk. *The observation that star formation ceased* ~ 100 *Myr ago therefore rules out stripping in the core and argues that stripping must be occurring locally.* This result is in agreement with simulations of the HI morphology and kinematics (Vollmer et al. 2006) which also argue for local stripping. Stripping so far out in the cluster shows either that gas stripping of galaxies in clusters is easier than the simple estimates of ram pressure imply (Kenney et al 2004), or that some galaxies experience extreme conditions due to a dynamic ICM (Dupke & Bregman 2006; Heinz et al 2006). In particular, NGC 4522 appears to be located between M87 and the M49 subcluster, which is likely in the process of merging with Virgo (Schindler et al. 1999; Shibata et al. 2001). Moreover, Shibata et al. (2001) observe a shock front in the ICM near the location of NGC 4522, suggesting that the local ICM has a high velocity. This makes it plausible that gas stripping is important for transforming galaxies well outside the cluster core, including at the interface between merging subclusters.

4.2. *Similarity to Higher-z K+A Galaxies*

The outer disk of NGC 4522 has strong Balmer lines and no emission, similar to K+A galaxies observed at higher redshift. While the outer disk of NGC 4522 shows a K+A spectrum, a global spectrum of this galaxy does *not* show the same signature, since it contains emission lines from the star-forming inner disk and absorption lines mostly from the stripped outer stellar disk (Gavazzi et al 2004). This makes it different from the K+A galaxies observed at higher redshift and more similar to the "e(a)" class (Dressler et al. 1999). Spectral modeling (Shioya et al. 2002) has suggested that the e(a) class may evolve into K+A galaxies, but some observations (i.e. Balogh et al. 2005) indicate that e(a) galaxies and K+A galaxies are morphologically distinct. There may be more than one way to make a K+A and e(a) galaxies, but the present observations show that ram pressure stripping *can* create a K+A or e(a) spectrum, either from total stripping (K+A) or partial stripping (e(a)). This shows that ram pressure is effective in rapidly terminating star formation and is capable of creating the post star formation spectra observed at higher redshift. It may be that, in the case of Virgo, the ICM is not dense enough to completely strip the gas from a massive galaxy in a single passage so that a central star-forming gas disk will remain after this stripping event ends. In the largest clusters, the ICM density is higher by a factor of ~ 10 and galaxy velocities are higher by a factor of ~ 2; this means that ram pressure is ~ 40 times higher in these clusters. In such clusters, it is likely that a galaxy like NGC 4522 would be completely stripped of its gas. In fact, Poggianti et al. (2004) have observed a striking correlation between K+A galaxies and the locations of X-Ray structure in the Coma Cluster, suggesting that we are observing such transformations there. Both these observations and our observation of NGC 4522 indicate that cluster processes are important for the creation of some K+A spectra. While K+A/e(a) galaxies may not all be created in clusters, it appears that at least one route for their formation is the termination of star formation by ISM-ICM stripping. Moreover, it appears that stripping can drive this transformation well outside the cluster core.

We gratefully acknowledge the indispensable discussions and advice of Jim Rose, which were critical at the early stages of this paper. We also would like to thank Pieter van Dokkum, Jacqueline van Gorkom, and Bernd Vollmer for comments that served to clarify the discussion. Finally, we wish to thank the referee for insightful comments and suggestions. This research is supported by NSF grant AST 00-71251.

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